IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Filled Transformers

Sponsor

Transformers Committee
of the
IEEE Power Engineering Society

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Abstract: Provides guidance for determining the hottest-spot temperature in distribution and power transformers built in accordance with IEEE Std C57.12.00-2000. Describes the important criteria to be evaluated by any thermal model that can accurately predict the hottest-spot temperature in a transformer. Provides guidance for performing temperature-rise tests with direct measurement of the hottest-spot temperatures, and explains the importance of developing an accurate thermal model to properly locate the temperature sensors.
Keywords: distribution transformer, hottest-spot temperature, power transformers, temperature rise test, thermal model

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Introduction

(This introduction is not part of IEEE Std 1538-2000, IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Filled Transformers.)

It is required by IEEE Std C57.12.00-1993 that the hottest-spot temperature rise not exceed 80 °C. The hottest-spot temperature rise at rated load is a necessary parameter for determining the loading capability of all transformers. Since there was no approved test or calculation method to demonstrate compliance with the IEEE standard, an IEEE Working Group on Hottest-Spot Temperature Rise Determination in Liquid-Filled Transformers was formed to develop this guide.

This guide provides information to determine the maximum (hottest-spot) temperature rise by calculation and testing. Modern computer technology permits calculation of hottest-spot temperature. Most manufacturers use computers for their design calculations, and it is reasonable to incorporate a thermal subroutine into the programs that would calculate hottest-spot temperature rises. Current personal computers have capabilities that were present only in mainframe computers decades ago. Fiber-optic temperature sensors now permit direct measurement of the temperature of a specific point. By prior analysis of the winding, the sensor can be placed to read the maximum winding temperature. For distribution transformers, thermal testing may be conducted using embedded thermocouples.

This guide applies to liquid-filled power, network, and distribution transformers manufactured in accordance with IEEE Std C57.12.00-1993. Although thermal gradients may be low in properly designed small (10–25 kVA) distribution transformers, the thermal gradients may not be low in the wide range of transformers classified as distribution transformers, which may extend in range to 5000 kVA.

IEEE standards documents are classified as

a) *Standards:* documents with mandatory requirements.
b) *Recommended practices:* documents in which procedures and positions preferred by the IEEE are presented.
c) *Guides:* documents in which alternative approaches to good practice are suggested but no clear-cut recommendations are made.

This document is classified as a guide. Documents with mandatory requirements such as standards use the verb *shall* whereas the other documents use the word *should*. This practice is followed in this guide unless the requirements are mandatory in IEEE Std C57.12.00-1993. Mandatory requirements taken from IEEE Std C57.12.00-1993 are enclosed in quotation marks.

This guide was produced by the IEEE Working Group on Hottest-Spot Temperature Rise Determination for Liquid-Immersed Transformers. At the time the guide was approved, it had the following membership:

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IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Filled Transformers

1. Overview

1.1 Scope

This guide provides guidance for developing mathematical models and test programs to determine the steady state maximum (hottest-spot) and average winding temperature rise over ambient for all liquid-immersed distribution, power, network, and regulating transformers manufactured in accordance with IEEE Std C57.12.00-2000.[1]

1.2 Purpose

IEEE Std C57.12.00-2000, subclause 5.11.1.1, states, "the maximum (hottest-spot) winding temperature rise above ambient temperature shall be determined by either

a) Direct measurement during a thermal test in accordance with IEEE Std C57.12.90-1999. A sufficient number of direct reading sensors should be used at expected locations of the maximum temperature rise as indicated by prior testing or loss and heat transfer calculations.
b) Direct measurement on an exact duplicate transformer design per a).
c) Calculations of the temperatures throughout each active winding and all leads. The calculation method shall be based on fundamental loss and heat transfer principles and substantiated by tests on production or prototype transformers or windings."

This guide describes recommendations for a manufacturer's test program or mathematical model to demonstrate compliance with the above requirements.

[1]Information on references can be found in Clause 2.

2. References

This guide should be used in conjunction with the following publications. When the following publications are superseded by an approved revision, the revision should apply.

IEEE Std C57.12.00-2000, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.[2]

IEEE Std C57.12.80-1978 (Reaff 1992), IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90-1999, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformers.

3. Definitions

3.1 average winding temperature rise: The arithmetic difference between the average winding temperature and the ambient temperature as determined from the change in the ohmic resistance measured across the terminals of the winding in accordance with the test procedures specified in IEEE Std C57.12.90-1999.

3.2 bottom-oil temperature: The temperature of the liquid as measured at an elevation below the bottom of the coils or in the oil flowing from the liquid cooling equipment.

3.3 bottom-oil temperature rise: The arithmetic difference between the bottom-oil temperature and the ambient air temperature.

3.4 core form transformer: A transformer in which those parts of the magnetic circuit surrounded by the windings have the form of legs with two common yokes.

3.5 directed flow: Indicates that the principal part of the pumped oil from heat exchangers or radiators is forced to flow through the windings.

3.6 distribution transformer: A transformer for transferring electrical energy from a primary distribution circuit to a secondary distribution circuit or consumer's service circuit.

3.7 flow direction: A pattern of flow in disc or helical windings caused by alternately blocking the vertical ducts inside and outside the winding to cause the liquid to flow in a zigzag pattern. This construction is used with either directed or non-directed flow transformers.

3.8 H-factor: A dimensionless number for predicting the maximum winding temperature rise over fluid due to increased eddy losses and other factors at the winding hottest-spot location.

3.9 hot-spot: A nonrecommended abbreviated term frequently used as a synonym for the maximum or hottest-spot temperature rise of a winding.

3.10 maximum (hottest-spot) winding temperature: The maximum or hottest temperature of the current carrying components of a transformer winding and leads in contact with insulation or insulating fluid. The hottest-spot temperature is a naturally occurring phenomena due to the generation of losses and the heat-transfer phenomena. It is the highest temperature inside the transformer winding and leads and is

[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

greater than the measured average winding temperature. All transformers have a maximum (hottest-spot) winding temperature.

NOTE—In this guide the hottest-spot rise is not considered to be due to localized manufacturing defects. Defects that affect long term performance or cause the hottest-spot rise to exceed the limits set in IEEE Std C57.12.00-2000 should be corrected.

3.11 maximum (hottest-spot) winding temperature rise: The arithmetic difference between maximum (hottest-spot) winding temperature and the ambient temperature.

3.12 network transformer: A transformer designed for use in a vault to feed a variable capacity system of interconnected secondaries. A network transformer may be of the submersible or of the vault type.

3.13 nondirected flow: Indicates that the pumped fluid from the heat exchangers or radiators flows freely inside the tank, and is not forced to flow through the windings.

3.14 oil: A shortened term for mineral oil that is a specially refined mineral-oil for use as an insulating liquid and coolant in transformers. For the purposes of this document, when terms such as “top oil rise” are used, “oil” should be considered synonymous with “fluid” since fluids other than mineral oil are used. See IEEE Std C57.12.00-2000.

3.15 power transformer: A transformer that transfers electric energy in any part of the circuit between the generator and the distribution primary circuits.

3.16 prototype transformer: A transformer manufactured primarily to obtain engineering data or evaluate manufacturing or design feasibility. Prototypes may be preproduction units or units typical of current designs manufactured for test purposes to obtain data to comply with changes in industry standards or for other reasons.

3.17 radiator: A fluid to air heat exchanging device attached to a transformer for the purpose of exchanging heat from the transformer fluid to the ambient air.

3.18 shell-form transformer: A transformer in which the laminations constituting the iron core surround the windings and usually enclose the greater part of them.

3.19 temperature rise: The difference between the temperature of the part under consideration (commonly the “average winding rise” or the “maximum (hottest-spot) winding temperature rise”) and the ambient temperature.

3.20 top-oil rise: *See:* **top-oil temperature rise**.

3.21 top-oil temperature: The temperature of the top layer of the insulating fluid in a transformer, representative of the temperature of the top fluid in the cooling flow stream, generally measured 50 mm below the surface of the fluid.

3.22 top-oil temperature rise: The arithmetic difference between the top fluid temperature and the ambient temperature. *Syn*: **top-oil rise**

4. Test methods

4.1 Direct measurement by fiber optic detectors

Fiber optic temperature detectors may be used to measure temperatures in power transformers. The probes may be removed or remain in the transformer winding for measurement of temperatures under operating conditions. Experience and data using fiber optic probes is given in the references of Annex A. Proper choice of the installation locations is crucial to accurately determining the hottest-spot temperature. The probable location of the hottest-spot should be determined by analysis of the eddy loss distribution, the oil flow distribution, and the heat transfer characteristics of the winding. Redundant sensors should be used at the expected hottest-spot location. A CIGRE survey [B16] reported that two to eight sensors would be adequate if placed in the winding where the higher temperature is expected, but for prototype transformers it was estimated that 20 to 30 sensors would be required. Some researchers have attempted to measure the temperature of the fluid in the winding ducts using fiber optic sensors. It is difficult to obtain a true measurement of the winding duct fluid temperature, and it is recommended that all probes be placed within the winding when a limited number of probes are available. The number of probes and strategic locations should be agreed upon between the purchaser and seller before the transformer is manufactured.

Thermal tests may be conducted at rated load in accordance with IEEE Std C57.12.90-1999. The thermal data may be used to verify the hottest-spot temperature performance for a specific design and to verify thermal models to be used for other designs. Data from tests at loads above and below rating will further assist in the development of thermal models to predict performance of other designs.

4.2 Direct measurement by thermocouples

For distribution transformers, it is feasible to install thermocouples in windings of prototype or actual transformer designs. If the thermal tests are conducted using the “short-circuit method,” the test voltage is usually less than 1000 V. Thermocouples can also be used on some distribution transformer designs when using the “loading back method,” which applies rated voltage. The thermocouple measuring junction is insulated with a thin piece of insulation and inserted between winding turns or layers. Thermocouples should be of a small size to minimize conduction errors and the build of the windings. Thermocouple diameters of 1 mm–2.5 mm are recommended. Due to the low cost of the thermocouples, it is practical to install a large quantity in the winding during the coil winding process. For three-phase transformers or two-legged single-phase units, temperature variations between winding phases or coils are considered minimal. Thus, all the thermocouples may be installed in one winding or coil assembly consisting of primary and secondary windings. The major consideration is that the thermocouples may alter the build of the winding. To assist in development of a mathematical model, thermocouples should be installed to determine temperature variations in circumferential and vertical directions as well as layer to layer.

Tests should include loads above and below rating to obtain useful data for refining the mathematical model and to predict the thermal performance of other designs.

For studies of core loss effects, it is necessary to perform thermal tests by the loading back method with full voltage on the unit. For this reason, it is usually feasible to install thermocouples in only the lower voltage winding, which is usually next to the core.

Due to the voltage hazard, the thermocouples must not remain if the transformer is placed in service. For small transformers, the test transformers are scrapped. For larger units, the windings with the thermocouples may be replaced, and after normal production tests in accordance with IEEE Std C57.12.90-1999, the transformer may be placed in service.

4.3 Prototype test data

During thermal tests on a prototype transformer, the hottest-spot rise may exceed the required value at the rated kVA set for the prototype. The thermal program should be refined based on the prototype data, and production transformer designs are then based on the refined program. Usually, additional thermal testing using thermocouples or fiber optic sensors in another prototype is not needed.

4.4 Test windings

Test windings may be used to obtain data on large power transformers or distribution transformers. See Pierce [B10] for an example. The windings are wound in a noninductive manner so that normal transformer operating voltage is not present. Laboratory or shop power supplies may be used in combination with a transformer to obtain the necessary current. In addition, the winding wire size, material, and number of turns are designed to give the required heat to conduct the thermal tests. The considerations for number of thermocouples, location, and size discussed in 4.2 are also applicable for tests conducted on test windings.

Thermal testing conducted under laboratory conditions using test windings gives useful data on the heat transfer characteristics. However, with the noninductive winding, the only eddy losses present are skin effect losses which are extremely small at 60 Hz. Thus, thermal tests using test windings do not simulate the additional losses due to high eddy losses in the ends of the windings of large power transformers. These additional eddy losses should be considered in the final mathematical model.

5. Mathematical models to predict temperature distributions and hottest-spot rises

5.1 Fundamentals

This clause describes recommendations for a manufacturer's thermal model to demonstrate compliance with the hottest-spot temperature rise limits. The manufacturer should utilize a proven thermal model to locate and calculate the hottest-spot temperature rise in each active winding, and all leads, under rated conditions. The calculation of the hottest-spot temperature rise, using a model that meets the recommendations of this guide should be based on the detailed design knowledge available to the manufacturer. In each case, it is imperative that the manufacturer have data readily available to demonstrate that the calculated values are supported by experimental testing. As required by IEEE Std C57.12.00-2000, "the model shall be based on fundamental loss and heat transfer principles..." The mathematical model should consider the dimensions of all components affecting the losses and heat transfer. General allowances for each element of the hot spot model are not adequate.

The mathematical model should consider

a) Heat transfer in and from the radiators or heat exchangers and its effect on fluid temperature rise.

b) The fluid flow within the winding ducts.

c) Fluid flow interactions with radiators and winding.

d) The distribution of losses within the winding.

e) Conduction heat transfer effects within the winding caused by different insulation sizes and the length of the electrical conductors forming the winding.

5.2 Radiator or heat exchanger heat transfer

The heat transfer and fluid flow within the radiators, heat exchanger, and tank should be considered to determine the average fluid rise over ambient. Radiation and convection heat transfer should also be considered. The number of radiators, heat exchangers, fans, and pumps should be considered. The effect of quantity of radiators, fans, and heat exchanger may be determined by thermal tests on transformers with different arrangements and the data correlated. The overall performance, which determines the average fluid temperature rise, is the important factor. Calculation of flow rates within each individual heat exchanger is not required since the temperature distribution within the heat exchanger is not critical for determining the winding temperatures. These factors may be of consideration to a manufacturer wishing to improve the thermal performance of the heat exchanger.

Consideration of the overall friction and pressure drop effects is important for determining the overall flow rate and thus the top and bottom fluid temperature rise.

5.3 Fluid flow within the winding

Conductors surrounded by fluid at the top fluid temperature will have elevated temperatures. An accurate method of calculating the temperature of the fluid throughout the winding is essential to determining the hottest-spot temperature. The heat transfer, flow rates, and resulting fluid temperature should be modeled for each cooling duct. These calculations should account for fluid flow through parallel paths, or through separate ducts, which join for the local heat transfer rate and the adjacent conductor temperature. The program should consider the quantity, location, and size of the cooling ducts and fluid properties.

5.4 Fluid flow between heat exchangers and winding

At steady state, the overall fluid flow through the winding ducts and the outside of the winding equals the fluid flow through the radiators and down the inside tank wall. This flow determines the top and bottom fluid rise and should be considered in the thermal model.

5.5 Loss distribution

The analysis should account for the nonuniform distribution of losses within the winding due to eddy loss and temperature variations. One of the principal causes of extra local loss in the winding conductors is radial flux eddy loss at the winding ends, where the electromagnetic field intercepts the wide dimension of the conductors. The total losses in the subject conductors should be determined using the eddy and circulating current losses in addition to the dc resistance loss. Leakage field analysis may be used to determine the magnitude of the flux and the resulting losses. Connections that are subject to leakage flux heating, such as coil-to-coil connections and some tap-to-winding brazes, should also be considered.

5.6 Conduction heat transfer

The analysis should account for the conduction heat transfer effect of conductor size, length, and the various insulation thickness used throughout the winding.

5.7 Considerations for core-form power transformers

Core-form power transformers utilize round windings of the layer or disc type as illustrated in Figure 1. In addition to the factors listed in 5.1–5.6, factors specific to these winding types are described in the following subclauses.

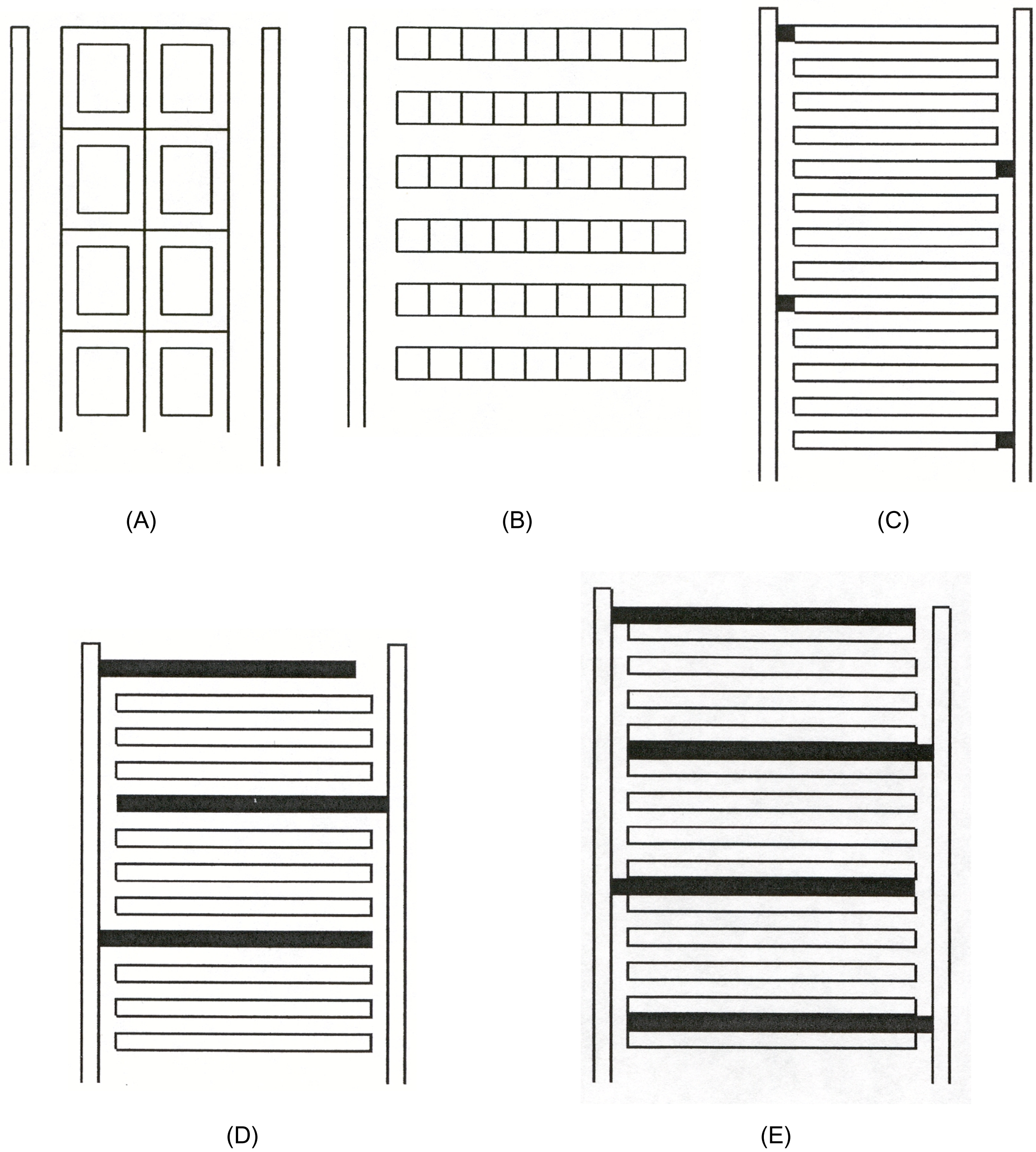

Figure 1—Winding arrangements for core-form power transformers

5.7.1 Layer type windings

The layer type winding illustrated in Figure 1, part (A) consists of turns of wire wound in multiple layers with vertical cooling ducts. Compared with the disc type windings in Figure 1, parts (B) through (E), this winding is simpler to analyze. In addition to variables listed in 5.1–5.6, other factors to consider are

a) Flow rates in multiple cooling ducts.

b) Multiple layers and multiple cooling ducts that affect the heat flux into each cooling duct. The heat flux from one side of the cooling duct may be different from the other side.

c) Layer insulation may be a different thickness throughout the winding.

d) Insulation next to the cooling duct affects the heat transfer.

5.7.2 Disc winding without flow direction

A section of a simple disc winding without flow direction is illustrated in Figure 1, part (B). This winding is used in nondirected flow transformers, where the fluid is not forced to flow through the winding. Pumps may be used to circulate the fluid through the tank and heat exchangers lowering the top fluid temperature in the tank. This also affects the flow rate through the vertical ducts of the winding. The fluid flows through the winding by natural convection. The fluid flow is principally through the vertical ducts with no particular tendency to flow through the horizontal ducts. Slight dimensional variations in the disc sections tend to cause some horizontal fluid flow which is different across each section. Temperature profiles for this configuration are shown in Pierce [B10]. The analysis should take into account fluid flow patterns that result in reduced flow or complete stagnation in some regions. Because of the random nature of the flow, this winding is the most difficult to analyze.

5.7.3 Disc winding with flow direction

To cause flow across the horizontal sections, flow diverting washers or barriers are introduced into the vertical duct to cause the flow to be in a zigzag fashion up the winding. Flow direction within the winding is commonly used on transformers with directed flow and is also used on transformers with nondirected flow. Different schemes are used to introduce the zigzag flow. Some of these schemes are illustrated in Figure 1, parts (C), (D), and (E). There are variations of these schemes and partial flow diversion has been considered.

In the arrangement of Figure 1, part (C) the flow directing barriers are attached to the end strands of the disc section. The loss of the vertical cooling surface for the disc sections with the barrier should be considered. Flow directing washers with cooling ducts above and below the washer may also be used as shown in Figure 1, part (D). Another scheme is illustrated in Figure 1, part (E) where the distance between all disc sections is the same and the flow directing washer is installed in the space between disc sections. The flow directing washer blankets the surface of the conductor and restricts the heat transfer into the fluid and raises the local temperature of the winding conductor. The thermal model should account for this localized heating.

For all these schemes the fluid flow velocity is different between the various disc sections and should be considered. Examples of temperature and velocity profiles are given in Oliver [B62].

5.7.4 Other considerations for power transformers

Local flow restrictions should be considered. Even windings with flow direction may have some local flow restrictions. Regions where leads exit the windings through end blocks should be investigated. The analysis should account for added tape where conductors exit windings; added tape and barriers on leads outside the windings near ground, or through a bushing; extra conductor insulation on end turns; and areas covered by insulation board. Winding conductors exiting through the end insulation may have extra insulation.

5.8 Considerations for distribution and small power transformers

Distribution and small power transformers usually utilize rectangular windings. Some manufacturers may use circular coils for select designs. Fluids other than mineral oil are also used. To minimize the amount of material used and to improve short-circuit strength, the layer insulation contains an adhesive. The portion of the windings under the core iron are pressed and baked to bond the adhesive to the coil conductor and layer insulation. Cooling duct arrangements may differ from power transformers in that not all ducts extend completely around the winding. Some cooling ducts are located only in the portion of the winding outside the core iron typically referred to as “end ducting.” For this reason, some refer to this winding as a “collapsed duct rectangular winding.” To reduce the hottest-spot temperature, some transformers may contain a few

ducts (termed annular ducts) that extend completely around the winding. For these annular ducts to be effective, allowance must be made for fluid to enter and exit the portion of the duct under the core iron.

A quarter section of a winding is illustrated in Figure 2. The winding may consist of a secondary and primary coil assembly. For small distribution transformers, the winding arrangement may consist of an inner secondary winding, primary winding, and an outer secondary winding. The windings are wound tightly over each other with insulation between the windings, although ducts are sometimes used between windings. The space between the inner secondary winding and the core is small and the insulation under the winding may be in contact with the core. The adjacent windings of three-phase units or two-legged single-phase units usually touch and may contact the outer core legs of shell type or three-phase five-legged core-type units. Cores may be either stacked or wound.

The collapsed duct arrangement causes a circumferential temperature gradient from the center of the winding with no ducts under the core iron to the center of the winding outside core iron where cooling ducts are located. In addition, thermal gradients are present between layers. The vertical temperature gradient is due to the oil flow within the cooling ducts and the outer surface of the windings.

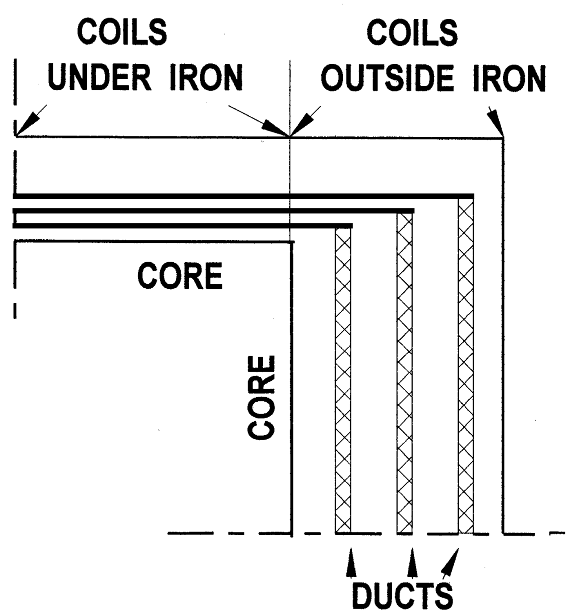

Figure 2—Quarter section of rectangular winding

The following factors should be considered in a winding heat transfer model for distribution or small power transformers:

a) Fluid properties (i.e., viscosity, thermal conductivity, coefficient of thermal expansion, density, and specific heat).

b) Quantity, location, and size of cooling ducts.

c) Heat flux from each side of the cooling duct is different. The heat flux also varies with the particular cooling duct and varies circumferentially along a given duct.

d) Heat flow across layers should be considered. Layer insulation thicknesses may vary throughout the winding.

e) Circumferential heat flow from the portion of the winding under core iron to the portion of the winding outside core iron should be considered.

f) Heat flow between the various windings and the core occur and should be considered.

g) An accurate determination of the dimensions of the various parts of the winding is important to predict temperature rises. To properly allow for conduction heat transfer and loss generation, it is of particular importance to determine the dimensions of the parts of the winding where cooling ducts are not present. Dimensions of the parts of the winding where cooling ducts are located can be easily determined from the dimensions of the cooling duct assemblies.

h) Layers and turns in the tapped-out parts should be considered.

6. Determination of hottest-spot rise from production thermal tests without direct measurement of hottest-spot temperature

Thermal tests are usually performed without direct measurement of the hottest-spot rise. There are no methods or equations to obtain hottest-spot rise from measurements of fluid temperatures and average winding temperature rise by resistance during standard commercial tests in accordance with IEEE Std C57.12.90-1999. The manufacturer's thermal model and test data using direct measurement on other units may be used to determine the hottest-spot rise from the production thermal test data.

The thermal test data may be used to determine the hottest-spot rise by means of the following equations.

$$H = \frac{\Delta\Theta_{H,*} - \Delta\Theta_{TO,*}}{\Delta\Theta_{W,*} - \Delta\Theta_{AO,*}} \tag{1}$$

$$\Delta\Theta_{AO,T} = \frac{\Delta\Theta_{TO,T} + \Delta\Theta_{BO,T}}{2} \tag{2}$$

$$\Delta\Theta_H = \Delta\Theta_{TO,T} + H[\Delta\Theta_{W,T} - \Delta\Theta_{AO,T}] \tag{3}$$

where

H is a dimensionless factor whose value is greater than 1.0

$\Delta\Theta_{AO,T}$ is average fluid rise over ambient for the unit tested, °C

$\Delta\Theta_{AO,*}$ is average fluid rise over ambient determined by analysis or from tests on similar units, °C

$\Delta\Theta_{BO,T}$ is bottom fluid rise over ambient for the unit tested, °C

$\Delta\Theta_{BO,*}$ is bottom fluid rise over ambient determined by analysis or from tests on similar units, °C

$\Delta\Theta_H$ is winding hottest-spot rise over ambient, °C

$\Delta\Theta_{H,*}$ is winding hottest-spot rise over ambient determined by analysis or from tests on similar units, °C

$\Delta\Theta_{TO,T}$ is top fluid rise over ambient for the unit tested, °C

$\Delta\Theta_{TO,*}$ is top fluid rise over ambient determined by analysis or from tests on similar units, °C

$\Delta\Theta_{W,T}$ is average winding rise over ambient for the unit tested, °C

$\Delta\Theta_{W,*}$ is average winding rise over ambient determined by analysis or from tests on similar units, °C

Errors in prior testing using direct measurement of hottest spot can lead to erroneous values of the H-factor. An error on the low side of the average winding rise gradient with an accurate hottest-spot value gives a high value of the H-factor. A measurement error on the low side for the hottest-spot gradient and an accurate value of the average winding gradient gives a low value of the H-factor. Hottest-spot temperature rise measurements less than the average winding rise have been reported with fiber optic detectors. Care should be exercised to correctly measure hottest-spot rise.

Many factors influence the ratio of hottest-spot rise to average winding rise. Many of these factors are described in this guide. By using a combination of mathematical analysis combined with testing using embedded detectors, a manufacturer may develop H-factors for different designs.

This should be acceptable if the H-factor for a specific design is based on the manufacturer's experience from analysis and tests on past designs. It is the manufacturer's responsibility to choose the correct H-factor. Statistical analysis of a number of analyses and tests might be used. The choice of an unrealistic high value penalizes the user in determining loading capability. Unrealistic low values should also be avoided. A discussion of the variation of the H-factor is given in Annex C.

7. Documentation and acceptance criteria

IEEE Std C57.12.00-2000, subclause 5.11.1.1, states, "The maximum (hottest-spot) winding temperature rise above ambient shall be included on the test report with the other temperature rise data. A note shall indicate which of the above methods was used to determine the value." The "above methods" are also listed in 1.2 of this guide. When direct measurements of hottest-spot temperatures are not performed, the manufacturer's thermal model and/or prior tests should be the only criteria to determine the hottest-spot rise. Other methods should only be used by agreement between the manufacturer and purchaser in the purchasing contract.

A detailed report of calculations should not be required to be submitted with the test report. It is expected that manufacturers will incorporate the thermal model as a subroutine in their computer design programs. Some manufacturers may choose as an option to supply additional information from the computer subroutine to further substantiate their performance claims.

Reports describing the manufacturer's thermal program and tests are highly proprietary. Summary reports describing the thermal model and a comparison of the predictions vs. test results should be available for review at the manufacturer's plant or at another location by prior agreement.

Annex A

(informative)

Bibliography on experimental testing to predict or confirm transformer thermal performance

Information on experimental apparatus, procedures, and test data is also given in [B43], [B44], [B45], [B46], [B51], [B56], [B65], [B67], [B68], [B70], [B72], [B74], and [B75] of Annex B. This bibliography is divided into two parts, as follows:

a) Thermal testing by methods other than fiber optics

b) Testing by methods using fiber optic temperature detectors

A.1 Testing by methods other than fiber optics

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Annex B

(informative)

Bibliography on modeling of transformer thermal performance

This bibliography was compiled to assist in development of mathematical models to predict the thermal performance of transformers. Finite difference methods are described in many sources on heat transfer. The book by Thomas [B33] is a modern reference. Schenck [B31] is listed because implementation in computer programs is described. The references on conduction analysis have limited application for large distribution or power transformers. They could be useful for very small transformers and were listed to give a comprehensive bibliography. References on mathematical modeling of other than liquid filled transformers were included because the techniques could be applicable to all types of transformers. These references may also include experimental methods. References on modeling of transformers cooled by two phase flow were not included because of the uniqueness of the heat transfer mechanism.

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Annex C

(informative)

Determination of hottest-spot rise from tests without direct measurement

C.1 Introduction

It would be desirable if the hottest-spot rise could be determined from measurements of fluid temperatures and average winding rise by resistance during standard commercial tests in accordance with IEEE Std C57.12.90-1999. Two methods have been proposed, the “multiflow method,” and the “IEC method.” The “multiflow” method was based on considerations of oil flow within the winding. The “IEC method” is based on a consideration for the higher eddy losses at the top of the winding.

C.2 Multiflow method

The multiflow method to determine hottest-spot rise was first proposed by Carruthers and Norris [B81]. They proposed that the hottest-spot rise could be determined from the following equations:

For ON cooling

$$\Delta\Theta_h = 1.1\Delta\Theta_r - 1.1\Delta\Theta_{mwo} + \Delta\Theta_{to} \tag{C.1}$$

For OF and OD cooling

$$\Delta\Theta_h = 1.1\Delta\Theta_r + 0.9\Delta\Theta_{mwo} - \Delta\Theta_{bo} \tag{C.2}$$

where

$\Delta\Theta_r$ is temperature rise of a winding by resistance

$\Delta\Theta_{mwo}$ is average temperature rise of oil inside winding ducts

$\Delta\Theta_{to}$ is top oil temperature rise

$\Delta\Theta_{bo}$ is bottom oil temperature rise

It was assumed and proposed that the average oil rise inside the winding ducts could be obtained from the asymptotic value of the winding cooling curve. Others have proposed that it could be obtained directly by inserting probes into the winding ducts.

Direct measurement data using fiber optic detectors presented by Lampe [B86] and Lampe [B84] showed considerable deviation from values calculated using the multiflow method.

C.3 IEC method

Equations for estimating the hottest-spot temperature rise at steady state for loads above rating were given in the IEC Loading Guide 354 [B93]. Although these are only estimating equations, they are commonly called

"The IEC method" in the United States. It does *not* appear in the IEC performance standard IEC 60076-2 (1993-04) [B92] as an approved method or requirement to calculate winding hottest-spot temperature rise. It is however discussed in a subclause of an informative Annex B whose title is "Transient loading—mathematical model and testing." In IEEE Std C57.12.00-2000, it is required that the hottest-spot rise not exceed 80 °C. There is no requirement in IEC 60076-1 (1993-03) [B91] or IEC 60076-2 (1993-04) [B92] to meet a specified hottest-spot temperature rise. Since there is no IEC performance requirement for hottest-spot temperature rise, the purpose of the information in Annex B of IEC 60076-2 (1993-04) [B92] and IEC 60354 (1991-10) [B93] is to provide information for user calculations of loading capability. Users of transformers manufactured to IEEE Std C57.12.00-2000, could use 80 °C for the rated hottest-spot rise in their loading calculations. It is a misconception that the so-called "IEC method" is an approved IEC method to determine the hottest-spot rise for the purposes of complying with performance requirements.

For natural flow, the IEC equation is based on multiplying the difference in average winding rise and average oil rise by an H-factor and then adding it to the top oil rise. For forced oil transformers, it is based on multiplying the difference in average winding rise and average oil rise in the winding by an H-factor and then adding it to the bottom oil rise and the oil rise at the top of the winding ducts. The oil rise in the winding duct is determined from the asymptotic value of the winding cooling curve. The H-factor is to allow for the higher eddy loss at the end of the winding.

To prepare typical loading tables, the 1991 edition of IEC 60354 (1991-10) [B93] assumed a factor of 1.1 for distribution transformers and 1.3 for power transformers. Annex B of IEC 60076-2 (1993-04) [B92] states, "In large transformers there is considerable variation depending on design, and the manufacturer should be consulted for information, unless actual measurements are carried out..."

A 1995 CIGRE Electra article [B89] giving experimental results using fiber optic data showed that the hot spot factor ranged from 0.51 to 2.06. Values less than 1.0 are an obvious error. Although the mean value for power transformers was close to 1.3 the conclusion was that the factor cannot be represented by a single constant. The conclusions stated

"A utility with no overload specification that wants to use the loadability of its new transformers therefore has two choices:

— Measure the hot spot directly and, in the case of similar transformers, devise a thermal model of the hot-spot according to the design.
— Use the manufacturer's calculated value deduced from knowledge of his design."

A companion 1995 CIGRE Electra article [B90] described attempts to determine analytically the H-factor based on electromagnetic concepts. The study group concluded that it was not reasonable to recommend any formula for the H-factor.

Calculations of the H-factor for distribution transformers given in Pierce and Holifield [B63] showed a range from 1.018 to 1.741 for ratings from 15 kVA single phase through 2500 kVA three phase.

C.4 Summary

The two methods described in this Annex gave variations between test and calculation by using a single value of the constants in the equations. The multiflow method considered the variable of variation of oil temperature and the IEC concept was based on considerations of eddy loss variation and oil temperature at the top of the winding. Equation (1), Equation (2), and Equation (3) of this guide with a variable H-factor were proposed as a suitable method. This should be acceptable if the H-factor for a specific design is based on the manufacturer's experience from analysis and tests on past designs.

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